On the edge: a multilevel perspective on innovation complexities and dynamic attractors in the supply network

International Journal of Operations & Production Management

Iryna Malacina and Katrina Lintukangas
Business School, LUT University, Lappeenranta, Finland

Received 24 January 2024
Revised 21 May 2024
28 August 2024
16 September 2024
Accepted 16 September 2024

Abstract

Purpose – In innovation management, the complexity inherited in the supply network may be necessary for success. This study aims to holistically examine innovation complexities and system attractors within a hierarchically nested supply network and explore how they dynamically interact and influence adaptive innovation processes.

Design/methodology/approach – Taking a complexity theory perspective, we employed a methodological bricolage approach using a single case study with multiple embedded units of analysis – namely, a supply network encompassing 36 firms. We drew upon primary data obtained from 42 interviewees and rich secondary data, and we employed a temporal exponential random graph model to examine the micro-foundations of the evolution of the sampled supply network over a decade.

Findings – This study presents a comprehensive overview of the innovation complexities—relational, temporal, dynamic, operational and structural – and how they manifest within a supply network. It also identifies three systemic attractors – point, periodic and strange – and elucidates their relationships with the complexities and their impact on innovative supply network dynamics. The resulting conceptual framework and working propositions provide a detailed perspective on the complex interplay between balanced order and chaos and the potentially unbalanced innovation states within a supply network.

Originality/value – This research offers an in-depth perspective on the innovation complexities and dynamic attractors within a supply network from a holistic, multilevel perspective. It advances complexity theory and deepens the understanding of supply networks as complex adaptive systems.

Keywords Innovation complexities, Supply network, Methodological bricolage, Systemic attractors, Exponential random graph modeling

Paper type Research paper

1. Introduction

A firm's supply network (SN) can be an important source of innovation (e.g. Bellamy *et al.*, 2014; Sharma *et al.*, 2020). Collaborating with SN partners can benefit firms seeking to develop innovative products and processes (e.g. Azadegan and Dooley, 2010; Winter and Lasch, 2016). By combining knowledge and resources, sharing costs and risks, and creating operational synergies, these relationships can provide valuable opportunities for successful innovation.

SNs are not simple systems. They are complex adaptive systems (CASs) composed of various interconnected actors and are "emergent, self-organizing, dynamic, and evolving" (Choi *et al.*, 2001, p. 364). The SN's inherent complexity translates into the innovation

This work is supported by the Finnish Foundation for Economic Education grant. The authors would like to thank Johannes Dahlke and Minelle Silva for their valuable and constructive feedback on the earlier version of the paper.

International Journal of Operations & Production Management
Emerald Publishing Limited
0144-3577
DOI 10.1108/IJOPM-12-2023-0929

complexities firms face when developing new products or processes. Furthermore, the innovation itself adds yet another layer of complexity.

Innovations are inherently complicated and probabilistic because of the uncertainties associated with their implementation (Quinn, 1985; Rickards, 1999). These uncertainties stem from the fact that future events do not follow the course of the past and that knowledge of the future is always incomplete (Jalonen, 2011). Although the innovation process is complex and chaotic, it is not random (Cheng and Van de Ven, 1996). Since a tight relationship exists between chaos and order, innovation can be coordinated in the desired direction (Dolan *et al.*, 2003). Chaos creates innovation (Handy, 2001); hence, the firm's ability to learn from and navigate the innovation complexities inherited in SNs may be more valuable than completely resolving them.

The idea of innovation management with controlled chaos is not new (e.g. Quinn, 1985; Cheng and Van de Ven, 1996; Jayanthi and Sinha, 1998). For more than 2 decades, research has sought to address the possibility of managing innovation complexities by investigating techniques that improve innovation performance. It has discovered methods that offer practitioners a comprehensive toolset that may help predict and explain the outcomes of different innovation management approaches. However, a fundamental misalignment seems to be developing between traditional organizational management approaches and the chaotic nature of innovation.

The traditional view relies on an intuitive way of resolving a system's complexity by examining and explaining its separate parts (Dolan *et al.*, 2003; Nair and Reed-Tsochas, 2019). However, this approach does not offer a holistic understanding or strategy for managing a complex system such as SN (Choi *et al.*, 2001). The alternative complexity perspective views such a system as dynamic and complex and focuses on the set of rules that influence its behavior (Stacey, 1995; Anderson, 1999). The complexity approach proposes that instead of avoiding chaos, an organization must embrace and use it to self-organize the system (Dolan *et al.*, 2003). An organization may coordinate chaos and anchor it to the desired direction through attractors or patterned behaviors (Jayanthi and Sinha, 1998; Dolan *et al.*, 2003). In the context of SNs, attractors are underlying patterns (Choi *et al.*, 2001) that often appear naturally and anchor the adaptive behavior of the actors within the SN and the SN at large. We suggest that by recognizing these patterns, firms may balance chaos and order to utilize the full potential of innovation complexities within SN.

In line with Choi *et al.* (2001) and Dolan *et al.* (2003), we use analogies from natural sciences (i.e. physics) to create new insights, as suggested by Gruner and Power (2023). We move beyond a single level of analysis to multilevel analysis (Carter *et al.*, 2015) and study the innovation complexities and attractors both on the firm level and SN level. Our approach enables a deeper understanding of the SN's functioning and the interconnections between its hierarchically nested levels (Carter *et al.*, 2015) and captures SN's behavior as CAS. We adopt the theoretical lens of complexity theory, which accounts for a system's multilevel structure, dynamism, and equifinality (e.g. Simon, 1962; Anderson, 1999; Choi *et al.*, 2001). In particular, we seek to answer the following research question: How do innovation complexities and attractors dynamically interact and influence innovation within a hierarchically nested supply network? Specifically, we aim to identify the innovation complexities and patterned behaviors present in the SN and their potential interactions.

To answer this question, we employed a methodological bricolage approach (Pratt *et al.*, 2022) in a case study of a hierarchically nested SN with multiple embedded units of analysis—namely, the 36 organizations embedded in the SN. The data collection involved 42 interviews with the organizations' representatives and extensive secondary data. To understand the dynamic evolution of the SN under investigation, we utilized the temporal exponential random graph model (TERGM), a class of social network methodologies.

Accordingly, we offer a detailed overview of the innovation complexities—relational, temporal, dynamic, operational, and structural—and how they manifest within the SN. We also outline three types of systemic attractors—point, periodic, and strange—and their relationships with innovation complexities. The resulting conceptual framework and working propositions provide a comprehensive perspective on the complex interplay between balanced order and chaos and the potentially unbalanced states of innovation.

This study makes several theoretical contributions. First, we advance complexity theory by holistically examining the five types of innovation complexities within SN, extending the seminal works of Choi *et al.* (2001) and Nair *et al.* (2016). Second, we define dynamic attractors within SN and expand our understanding of their correlation with innovation complexities. Although recognized in earlier works (e.g. Jayanthi and Sinha, 1998; Dolan *et al.*, 2003), these phenomena have garnered little research attention. Finally, we extend existing SN research (e.g. Kim *et al.*, 2011; Bellamy *et al.*, 2014) by conducting a novel temporal network analysis with TERGM to better understand SN's adaptive and dynamic behavior.

2. Theoretical background

2.1 Complexity theory

As the name suggests, complexity theory is based on the notion of a complex system, which is "*made up of a large number of parts that interact in a non-simple way*" (Simon, 1962, p. 468). From the SN perspective, parts refer to elements such as material and information flows and actors such as suppliers and buyers (Kim *et al.*, 2011). A complex system is not only complex in its composition but also exhibits complex dynamic behavior (Simon, 1962; Choi *et al.*, 2001; Nair and Reed-Tsochas, 2019). The complex interactions within the system make precise predictions about the behavior of its underlying elements at a specific time point extremely challenging (Simon, 1962; Sharma *et al.*, 2020).

Anderson (1999) summarized the pillars of complexity theory with several assumptions particularly relevant to our research question. First, processes within a system that appear random may revolve around observable patterns or *attractors*. In the SN context, attractors may be understood as behaviors or tendencies that emerge within different layers (or across the whole network) due to interactions between SN parts. Keiretsu (a network of interconnected firms that collaborate through cross-shareholding and close relationships) can be an example of an attractor or a stable, recurring pattern of behavior for Japanese firms (Choi *et al.*, 2001). Second, these processes can be sensitive to *initial conditions*, which is the starting state of a system before its development over time. For example, the physical location of SN is an initial condition that determines the proximity of resources and partners. Third, system parts cannot be studied in isolation, as patterns emerge at *different levels*; hence, multiple-scale descriptions are necessary. In the SN context, this would mean that, at a minimum, both the SN level and the firm level would be examined. Finally, systems usually tend to evolve toward *order* instead of disorder. For instance, firms in SN may prioritize stability and predictability in their innovation management, even when a more flexible or chaotic approach might lead to higher innovation outcomes.

Complexity theory has yet to be fully explored in the SN context. The emergence and proliferation of environmental innovations in SNs, from the CAS perspective, have been described by Nair *et al.* (2016). Other recent works following Choi *et al.*'s (2001) conceptualization have addressed supply chain learning (Wang *et al.*, 2023) and sustainable supply chain management (Najjar and Yasin, 2023). Nevertheless, limited research has focused on innovation complexities in SN, and even fewer studies have addressed the pillars Anderson (1999) suggested.

2.2 Attractors of a complex adaptive system

Chaotic systems are often characterized by either chaotic or stable behavior directed by attractors and exhibit nonstatic dynamics (Pryor and Bright, 2014). Attractors pertain to the distinctive trajectories shaped by feedback mechanisms, end states, boundaries, the overall vision of reality, and the equilibrium between stability and fluctuation that influences the individual actor's performance within the system (Pryor and Bright, 2014). A classic example of this phenomenon is the atmosphere. The atmosphere is a chaotic system, with the weather its behavior. While the weather appears unpredictable, the seasons follow a specific pattern (Platje and Seidel, 1993). Hayles (1990) emphasized an underlying qualitative order within CAS, even with individual path unpredictability, and formulated this phenomenon as "order within chaos." Similar to other systems, hierarchically nested SNs may initially seem chaotic and unpredictable, but they possess an innate capacity for self-organization that generates identifiable patterns despite their apparent randomness.

In the supply chain context, Choi *et al.* (2001) have defined attractors as long-term underlying behavior patterns embedded within the system. Building on this, in the SN context, we define attractors as *long-term underlying behavioral patterns that emerge within different levels of SN, driven by interactions between its parts, which anchors the SN to certain states*. These states can range from order to chaos, with SN aiming to operate at the "edge of chaos" (Choi *et al.*, 2001)—balancing stability and adaptability to remain both efficient and innovative.

CAS's most commonly described attractors are point, periodic, and strange attractors (Holbrook, 2003). A *point attractor* describes a state in which a system converges to a single point in its state space and remains there. For example, a firm may funnel information flows (i.e. new ideas) obtained from the SN into a centralized storage system for future use—a behavior pattern directed toward a single stable state of order. A *periodic attractor* (or recurrent cycle) describes a state in which a system oscillates or cycles through a set of states in its state space, eventually returning to its initial state and repeating the cycle. The period of a periodic attractor can be regular—that is, the system returns to the same state after a fixed time interval—or irregular. For instance, a firm might periodically recalibrate its operations and strategic vision with its suppliers to ensure alignment—a regular, repeated pattern of behavior. A *strange attractor* implies that a system fluctuates across various positions so that its state at any given time cannot be predicted, but the general position over time follows a coherent pattern (Holbrook, 2003). While strange attractors may be evidence of an underlying structure, individual trajectories do not provide the predictable stages of traditional life-cycle models (Fang and Levinthal, 2009). In the SN context, weak ties between firms represent a strange attractor, as these loose connections can create unpredictable dynamics across the network.

Prior research has established a basic understanding of attractors in organizations. Platje and Seidel (1993) described an organization as a chaotic system and the vicious circle of bureaucracy as a strange attractor. Thus, the organization's operations tend to converge toward the relatively stable behavior of a bureaucracy influenced by the general management's reluctance to deal with uncertainty. Platje and Seidel (1993) concluded that an organization requires another attractor that leads to flexible and creative behavior, such as the freedom of action for subordinates. Jayanthi and Sinha (1998) empirically observed system attractors in the case of high-technology manufacturing, measuring a plant's innovative performance over time. They observed that the performance settled into patterns that, while never identical, were bounded in a region of the phase space (strange attractor).

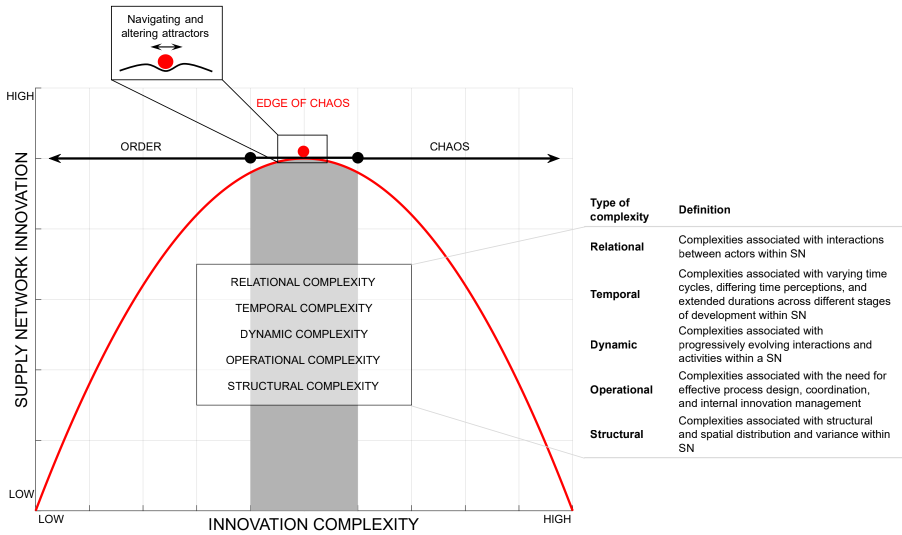
2.3 Innovation complexities within a supply network

Complex SNs naturally bring complexity to the innovation processes within them. This study defines innovation processes as activities aimed to develop product or process innovations. The success of innovation processes can be hindered by excessive control and unrestrained freedom, and the innovation potential thus lies at the intersection of order and chaos (Cheng and Van de Ven, 1996).

There are many studies suggesting balancing between various forms of complexity and innovation. For example, Sampson (2007), in the study of alliances, proposed that moderate complexity in relationships benefits innovation, while too much can lead to difficulties in coordination, reducing innovative performance. Seminal work by March (1991) points out that too much exploitation (routine, efficiency) stifles innovation, while too much exploration (experimentation) without enough exploitation can lead to inefficiency. Choi and Krause (2006) suggested a negative quadratic relationship between buyer innovation and the complexity of the supply base. They concluded that although complexity can stimulate innovation, excessive complexity can harm it. Sharma *et al.* (2020) have observed a negative quadratic relationship between the structural complexity of SN and the firm's innovative performance. In essence, moderate complexity may foster innovation by providing enough diversity and challenge to stimulate creative problem-solving. However, as complexity increases beyond a certain point, it can overwhelm the ability to coordinate and manage innovation effectively, leading to a decline in innovative outcomes.

Thus, we propose that SN innovation, which refers to the combined innovative performance of firms within the network in creating new products or processes, can take an inverted U-shape form, where the variation from optimum toward order or chaos reduces SN's innovation (Figure 1). In the early stages, increasing complexity tends to enhance innovation. When reaching the "edge of chaos," the level of complexity is optimal for innovation. Beyond the optimum, increasing complexity leads to inefficiency and slows down the innovation process. Around this "edge of chaos" emerge attractors or patterns that anchor the balance between order and chaos and influence the outcome of the innovation process within the SN (Pryor and Bright, 2014). SN innovation, therefore, may fluctuate from equilibrium with various types of complexities, as illustrated in Figure 1.

This study defines innovation complexities as multi-dimensional facets that firms encounter within SNs throughout the innovation process. *Relational* complexity refers to the entanglements and interactions between the social and material elements of the innovation process (Garud and Gehman, 2012; Garud *et al.*, 2013). This complexity can be substantive because of differences in perspectives and knowledge or conflicting interests and motives among SN actors (Klijn and Koppenjan, 2016; Callens, 2023). *Temporal* complexity refers to the existence of multiple temporal rhythms and progressions in the innovation process that generate asynchronies and diachronies (Van de Ven and Poole, 2005; Langley *et al.*, 2013;



Source(s): Authors' own creation

Figure 1. Equilibrium of innovation between order and chaos

Garud *et al.*, 2013). *Dynamic*, or evolutionary, complexity arises because of the continuously developing sociotechnical landscape. Pressure to change and events caused by chance create path dependency, in which consecutive developments determined by positive feedback loops lock the innovation process to progress in a certain direction (Garud and Gehman, 2012; Garud *et al.*, 2013). The innovation process is characterized by *operational* complexity, which refers to coordinating and orchestrating the innovation process to engage actors in innovation trajectories (Reypens *et al.*, 2021). Finally, institutional, or *structural*, complexity can arise because of divergent cultures and collaborative SN structures (Klijn and Koppenjan, 2016; Callens, 2023). Cultural complexity appears because of dissimilarities in organizational culture, where innovation processes are taking place (Khazanchi *et al.*, 2007; Callens, 2023; Garud *et al.*, 2013). To summarize, we holistically examine these five types of complexities (see Figure 1).

3. Research design

We applied a methodological bricolage approach (Pratt *et al.*, 2022) by combining several “analytic moves” to answer our research question. Methodological bricolage differs from traditional theoretical bricolage (e.g. Baker and Nelson, 2005) and encompasses “*the combining of analytic moves for the purpose of solving a problem or problems tailored to one’s own research project*” (Pratt *et al.*, 2022, p. 2019). Essentially, it empowers the researcher to move beyond the rigid use of a single methodology, instead inviting to think innovatively about method application and encouraging flexibility and creativity to meet the specific needs of the research. We chose flexible and situational methodological bricolage for several compelling reasons, such as its suitability for studying complex and dynamic phenomena (Pratt *et al.*, 2022) and the fact that it would give us the creativity necessary to adapt our methodologies as needed.

First, we employed a single case study with multiple embedded units of analysis (Yin, 2014). The case was the SN, with the embedded units comprising firms operating within the SN. We opted for a single case research design because it allowed us to explore the SN as an integrated whole while obtaining detailed contextual insights from individual firms. This approach was particularly valuable as our primary interest was in understanding the overarching processes and dynamics within the SN rather than the specific attributes of the individual firms (Yin, 2014). Consequently, while our analysis emphasized firms, it was consistently related to the SN at large.

Second, our initial case study revealed a pattern: The network appeared to converge with several innovative actors over time. This insight inspired us to integrate TERGM (Leifeld *et al.*, 2018; Leifeld and Cranmer, 2019), a social network analysis method that allows for modeling network evolution over time to examine these patterns from structural and temporal perspectives. Accordingly, the methodological bricolage approach was a natural fit for our research and enabled us to explore our research question more comprehensively.

3.1 Sample selection

Our sampling strategy mirrored standard SN study settings (e.g. Bellamy *et al.*, 2014) and included several steps. First, we identified very large manufacturing companies in Nordic countries using the Amadeus database, which provides information on over 500,000 private and publicly traded firms in European countries. The search string used was “*Operating revenue ≥ 100 € million AND Total assets ≥ 200 € million AND Employees ≥ 1,000 AND NACE codes 26–30 AND Country: Denmark, Norway, Sweden, Finland, Iceland*.” We chose very large companies as a starting point, as previous studies have described them as more innovative than smaller ones, owing to their high resource capacity in terms of personnel and budget (Stock *et al.*, 2002). We limited our sample to the Nordic countries because this region has been highlighted as best performing in terms of innovation (European Commission, 2022).

The resulting list included 60 companies, of which nine (15%) agreed to participate in our study and formed our initial sample. We then extended this sample with a list of first-tier suppliers, having asked interviewees to identify and describe several innovative suppliers with whom their company has collaborated. For this purpose, following Azadegan and Dooley (2010, p. 489), we defined innovative suppliers as firms that provide additional knowledge resources or capabilities that may enhance the innovative performance of their buyers. Hence, innovative suppliers are active in introducing improvements to products, processes, and/or technologies and are eager to present new ideas.

Additionally, we utilized publicly available data, such as news reports, to verify that the appointed suppliers were indeed high in innovative performance (e.g. innovation awards announcements). Accordingly, our sample was extended by 23 supplier companies willing to participate in the study. Despite nonresponse from four companies (E8, A3, C2, R1) to the initial request for interviews, they were included in the final sample due to the valuable information provided from the extensive secondary data and interviews with the buyers who designated them. As such, these companies were considered essential contributors to the overall analysis.

Next, we identified SN relationships between the 36 companies in our sample from 2012–2022 using primary interview data reflecting past relationships. We then cross-validated and augmented our dataset with information from the Eikon database, news articles, and public reports. We established specific criteria for selecting connections (edges) for inclusion in our sample, requiring a relationship between the firms that pertained to innovation collaboration, such as collaboration on new product development. The resulting dataset contains 36 companies connected by 241 relationships during a decade of observation (see Figure A1 in Appendix A).

In addition, we extended our study to include three third-party organizations (I1, I2, I3), such as innovation intermediaries, that interviewees explicitly identified as playing significant roles in the functioning of their innovation ecosystems. Appendix B summarizes the 36 firms that composed our final sample and three third-party organizations.

3.2 Data collection

Primary data were collected through 42 semi-structured interviews with key informants in the sample organizations. Whenever possible, more than one expert was interviewed in each organization. The semi-structured interview guide contained open-ended questions (Yin, 2014) and was developed based on the extant literature. Appendix C shows the interview guide. Depending on the interviewees' expertise, we modified the questions and focused more on a particular level of operations. We also asked follow-up questions about specific innovation collaboration cases.

The interviews took place between October 2021 and November 2022 and lasted approximately 44 min on average. To achieve data triangulation (Jick, 1979), the primary interview data were supplemented with secondary data (e.g. press releases from the companies' websites, news articles, annual reports, and publicly available interviews). Secondary data were mainly collected from the internet, focusing on data on the organizations' innovation strategies and initiatives. This included press releases on innovative buyer–supplier collaborations, supplier innovation awards, hackathons, and impacts on local environments, such as the opening of new factories as detailed in Appendix B.

Operational firm-level data from the 36 sample companies (excluding third-party organizations) from 2012 to 2022 were obtained from the Amadeus database. We focused on several factors that potentially impact the emergence of innovative partnerships among SN members. *Total sales* were measured as total operating revenue, and *firm size* was measured by the total number of employees. These factors were included in analysis as more profitable and large firms are more likely to be popular partners in the network and initiate partnerships themselves. Additionally, *total assets* were included as a proxy for more advanced equipment and operational processes. Total sales and assets were measured in million euros. To capture the potential path dependency that may prevent strategic change in firms over time (Elsayed, 2006), we included *firm age*. All items except firm age were logarithmically transformed to reduce skewness.

3.3 Data analysis

We applied an abductive coding strategy that aligned with our methodological bricolage approach. Initially, we identified broad thematic categories derived from the theoretical constructs of innovation complexities and attractors. Using MaxQDA software, we initiated deductive coding, assigning in vivo codes from our qualitative interviews and secondary data to these predefined themes. As our analysis advanced, we incorporated emerging second-order codes, allowing data-driven refinement within the theoretical themes. We continuously revised these second-order categories in response to the data, and because of this inductive approach, we achieved more organic and data-driven development of our coding schema. New categories were continuously added throughout this process.

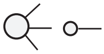
Additionally, we coded the relationships between complexities and attractors mentioned by interviewees or the secondary data. The first author led the data analysis and coding, with a second researcher independently coding portions of the data for validation, reducing potential bias and enhancing rigor (the inter-rater reliability was over 0.90). The coding tree, presented in Appendix D, underwent multiple reviews by the coauthors to ensure methodological robustness.

In our analysis, secondary data were treated with the same rigor as primary data, undergoing a systematic coding process to ensure consistency and enrich our findings. This included cross-verifying interview data with, for example, press releases and news articles, providing a comprehensive view that included the impact of SN dynamics on the broader environment (e.g. impact on local city infrastructure).

In our coding of innovation complexities, we were primarily guided by definitions of each complexity, as presented in Section 2.3. We adopted a specific approach for identifying dynamic attractors in the data. Our focus was mainly on change over time. For example, interviewees indicated that certain complexities, such as a limited choice of innovative suppliers, corresponded with specific behavior patterns over time, such as a bounded dyad between partners. Additionally, we explored whether these patterns occurred across different levels—both at firm (e.g. department) and network strata. For instance, convergence to the central node was observable at the firm and network levels. Lastly, we categorized the attractors into three types: point, periodic, and strange. This classification depended on whether the system converged to a single stable state, such as the storing of novel ideas by the firm; exhibited repetitive behavior, as seen in knowledge recalibration taking place in regular intervals; or displayed unpredictable behavior in which, despite the presence of a pattern, its specific state could not be clearly defined, such as in the case of weak ties.

Using TERGM, a class of social network analysis methodologies used to model the evolution of networks over time, we performed network analysis to capture the underlying processes and dynamics of the network. Appendix A shows the interconnections of the actors in our supply network case (Figure A1) and illustrates the network's temporal evolution from 2012 to 2022 (Figure A2). TERGM can be effectively utilized in the analysis of dynamic and complex networks, where ties between actors change over time and are influenced by different internal and external factors, such as nodal attributes, dyadic characteristics, and network processes (Leifeld *et al.*, 2018; Leifeld and Cranmer, 2019). It can be argued that TERGM is particularly suitable for operationalizing CAS's central concepts and principles (Robins *et al.*, 2007). We incorporated a combination of TERGM terms to model SN dynamics, as summarized in Table 1.

Table 1. Utilized TERGM terms

Configuration	Diagram	Description	Example
Structural effects			
Edges		A basic tendency for tie formation	Supplier-buyer relationship
Reciprocity		Tendency for symmetric network structure	Dyadic partnership
Actor effects			
The nodal effect (*size, revenue, total assets*)		Tendency of firms with a certain level of size, revenue, or assets to establish a link with another firm	Firms with higher assets are more likely to form innovative relationships in the network
Absolute difference (*age*)		Tendency of firms with similar or dissimilar ages to form a tie	Relationship between long-established firm and start-up

Source(s): Authors' own creation

4. Results

In this section, we present a summary of the key findings of our analysis. First, our focus is at a broad network level, detailing insights from the case study and temporal network analysis. Subsequently, we zoom in, offering a more in-depth perspective on innovation complexities and dynamic attractors.

4.1 Network analysis

Consistent with our expectations, we observed a dynamic network characterized by relationships forming and dissolving between firms (Appendix A; Figure A1). This dynamism aligns with previous findings describing SN as CAS (e.g. Nair *et al.*, 2016). Some ties remained longer, indicating a lasting collaboration toward innovation. Additionally, we observed SN becoming more interconnected with growing network centralization (Appendix A; Figure A2).

Our research focused on the last decade, yet the network we studied had evolved into its current form over a more extended period. Our data indicated that certain relationships and group formations within the network could be attributed to innovation processes and a historical tendency toward collaboration.

The TERGM analysis, detailed in Table 2, provided more insights into the micro-foundations that had influenced the formation of interorganizational links in our sample SN. A detailed analysis, including robustness checks, can be provided by the corresponding author upon request. The negative (positive) structural coefficient implies that the effect in the sample network appeared by chance less (more) often than expected. The negative *edge* coefficient suggests that the formation of innovative partnerships in the sampled network occurred less frequently than anticipated by chance. This outcome was not unexpected given that establishing such partnerships in SNs entails substantial resource commitments (e.g. Jajja *et al.*, 2017). The significant and positive *reciprocity* coefficient suggests a high likelihood of reciprocal relationships in the sample network. Out of the nodal actor effects utilized in the model, only the positive impact of *size* was statistically significant. This further confirms prior literature suggesting that large firms are more likely to engage actively in open innovation and outsource innovation activities to their partners (Winter and Lasch, 2016). The negative and significant coefficient of absolute differences in *age* indicates that firms in the sample network tended to form ties with other firms similar to them in terms of age. This may indicate that in

Table 2. SN formation, dependent variable: establishment of a tie between two firms

Term	Coefficient
Structural effects	
Edges	−9.28***
Reciprocity	2.38***
Actor effects	
The nodal effect (*size*)	0.25***
The nodal effect (*revenue*)	−0.08
The nodal effect (*total assets*)	0.12
Absolute difference (*age*)	−0.003**
Akaike information criterion (AIC) goodness of fit	2,208

Note(s): *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$
Source(s): Authors' own creation

our sample, firms in the SN did not often consider young firms, such as start-ups, as preferred innovative partners, possibly due to high risk aversion among the firms.

4.2 Case study results

In this section, we present our findings on innovation complexity in SNs. We address how these complexities shaped the SN as CAS and discuss the attractors that emerged with each type of complexity in our sample. Notably, not all complexities were linked to attractors in the data. Table 3 summarizes these findings. As shown in Table 3, complexities and attractors were categorized as either SN level or firm level.

4.2.1 Relational complexity. Most firms in our sample encountered relational complexities emerging from collaborations between different organizations or within a firm's departments. Although they were widespread, firms seemed to be well prepared to handle them. Our interviews revealed that firms faced complexities related to conflicting interests. Such complexities manifested as tensions between partners who may have had divergent views on issues such as the market potential of a new technology (B2), cooperation with competitors (M2), or leadership roles in a joint project (V3). However, we did not observe any attractor associated with this complexity.

Another common complexity that firms encountered was the limited choice of innovative suppliers. Often, the technology required for specific components was so specialized that companies were compelled to rely on single sourcing, which could lead to higher costs and intense competition for supplier access. The limited selection of potential innovative suppliers often led to the formation of a point attractor, manifesting as a bound dyad. Firms developed close relationships with the few technologically advanced suppliers they accessed—a trend noted across nearly all firms in the sample network. Such partnerships create mutual dependency but may also grant early access to technologies not yet available in the market (E4). The significant influence of this attractor was highlighted by a representative from E5. Once the firm identified a potential supplier capable of developing such a rare component ("*though it was not available in their market or in their catalog*"), it was determined to secure a partnership and establish a dyad as intertwined as possible.

Another typical relational complexity relates to ownership disparity, in which partners jointly contribute to innovation, but only one gains ownership and the associated benefits. This complexity was described by a representative of V2, whose firm had developed innovation in a consortium collaboration long ago, although the concept was now owned by one of the partners, which was "*doing further development and has commercialized it, and it is a really widespread concept that is used all over the world*." We did not observe any attractor associated with this complexity.

Table 3. Summary of findings – innovation complexities and dynamic attractors

Complexity	Definition	Level*	Associated dynamic attractor(s)	Level*	Definition
Relational complexity					
Conflicting interests	Tensions between partners who may have divergent views related to innovation and its outcomes	SNL	–	–	–
Limited choice of innovative suppliers	Limited number of alternative suppliers for innovation available on the market	SNL	Bound dyad (●)	SNL	Patterned behavior between buyer and supplier, where both parties maintain a tightly interdependent relationship, reinforced through consistent collaboration and repeated interactions
			Convergence to the central node in the SN (●)	SNL	Patterned behavior where firms within a SN increasingly direct relationships and dependencies toward a single, dominant node
Ownership disparity	Tensions associated with partners' collaborative contributions to innovation, where only one partner claims ownership and associated benefits	SNL	–	–	–
Partnership control	Tensions associated with more powerful partner holding the potential to dominate decision-making processes in collaboration	SNL	Systemic disentanglement (●)	SNL	Patterned behavior where firms intentionally disengage with the partner/s
Asymmetric engagement	Tensions arising from one partner's efforts to engage with another, less interested partner	SNL	Resonance state (⟲)	SNL	Regularly repeated patterned behavior where one party tries to increase the other party's interest in the relationship
Invisible internal interface	Subtle, often unrecognized points of interaction within the firm or between partners	FL	Connecting through an intermediary (●)	FL	Patterned behavior where a designated node or employee is established to systematically channel and manage information within

(*continued*)

Table 3. Continued

Complexity	Definition	Level*	Associated dynamic attractor(s)	Level*	Definition
					the firm or across the SN
Temporal complexity					
Timing of new product or process value	The challenge of making decisions based on the uncertain future value of new products or processes at a specific point in time	SNL	Temporal alignment (⟲)	FL	Regularly repeated patterned behavior where the firm synchronizes its future vision with its stakeholders'
			Knowledge recalibration (⟲)	FL	Regularly repeated behavior of a firm adjusting its own perspective and actions over time as new information is obtained
			Weak ties (⌘)	SNL	Dynamic characterized by infrequent and loose interactions playing a critical role in the diffusion of information and opportunities across the SN
Stretched innovation cycle	Challenge of planning for a new product's prolonged market presence which requires decisions that anticipate future conditions far in advance	FL	Observational learning (⟲)	FL	Regularly repeated behavior of a firm taking a passive role, watching the successes and failures of others before making its own move in a new domain
Innovation readiness rift	Complexity arising when a firm develops a new product, but stakeholders are not yet ready to adopt it, creating a temporal disconnect in the SN	SNL	Temporal alignment (⟲)	FL	Regularly repeated patterned behavior where the firm synchronizes its future vision with its stakeholders'
Mismatched development stages within the supply network	Complexity due to the need to synchronize the parts of SN with different development stages	SNL	–	–	–
Dynamic complexity					
Uncertainty about activities	Lack of visibility in SN, incomplete knowledge about	FL	Knowledge recalibration (⟲)	FL	Regularly repeated behavior of a firm adjusting its own

(*continued*)

Table 3. Continued

Complexity	Definition	Level*	Associated dynamic attractor(s)	Level*	Definition
in the other parts of the network	activities of other actors				perspective and actions over time as new information is obtained
			Actor reconfiguration (⌘)	SNL	Dynamic where more ambiguous segments of SN adapt in somewhat unpredictable ways
Selection pressure	Continuous pressure to outperform other actors in SN	SNL	Convergence to the central node in the SN (●)	SNL	Patterned behavior where firms within a SN increasingly direct relationships and dependencies toward a single, dominant node
Innovation blocking	Barries from other actors in SN preventing the firm from effectively utilizing the developed innovation	FL	–	–	–
Path dependency	Complexity associated with the need to deviate from the familiar way of thinking or operating	FL	–	–	–
Operational complexity					
Process design and required coordination	Complex management of various process designs and production of diverse product innovations	FL	Cross-applicability of technologies and components (⌘)	SNL	Dynamic where a firm leverages process developments from other unrelated industries to optimize and streamline its own operations
			Knowledge recalibration (⟲)	SNL	Regularly repeated behavior of a firm adjusting its own perspective and actions over time as new information is obtained
Internal innovation acquisition and dissemination	Complexity of holistic implementation of new solutions across diverse firm locations and potentially redundant management of multiple information channels within a firm	FL	Connecting through an intermediary (●)	FL	Patterned behavior where a designated node or employee is established to systematically channel and manage information within the firm or across the SN

(*continued*)

Table 3. Continued

Complexity	Definition	Level*	Associated dynamic attractor(s)	Level*	Definition
			Storing of novel ideas (●)	FL	Patterned behavior directing the innovative ideas toward a designated collection system
Stifling innovation within the firm	Complexity associated with the need to internalize innovations that had previously been developed in collaboration or fully by suppliers	FL	–	–	–
Economic viability of the innovation	Complex assessment of the economic viability of new solutions and the accurate	SNL	Preemptive innovation cycle (⟲)	FL	Regularly repeated behavior when the innovation process starts before feedback from the market is received or in parallel
Structural complexity					
Stretched supply network	Complexity of management of stretched SN	SNL	Connecting through an intermediary (●)	SNL	Patterned behavior where a designated node or employee is established to systematically channel and manage information within the firm or across the SN
Geographical variance in the supply base	Complexity of management of geographically diverse SN	FL	Systemic disentanglement (●)	SNL	Patterned behavior where firms intentionally streamline their supply base
			Societal–cultural conformity (⌘)	SNL	Dynamic where a firm seemingly adopts the culture of its environment or partners, aligning its behaviors and norms with external influences
Geographical variance in the firm	Complexity associated with the geographical variance within the firm	FL	–	–	–

Note(s): *Attributed to the most prominent level, while emergence at another level is possible; SNL – supply network level, FL – firm level; (●) point attractor; (⟲) periodic attractor; (⌘) strange attractor
Source(s): Authors' own creation

The analysis revealed complexity related to partnership control, which manifested in innovative collaborations among more powerful partners in the SN, as described in several interviews. This complexity has been associated with the point attractor of systemic disentanglement when a partner purposefully preserved the necessary complexity in the supplier base by, for example, not engaging in a specific dyad with a powerful partner, potentially gaining partnership control. This attractor was described by an interviewee who shared that although their firm, B1, had had the opportunity to secure supply of their novel solution with one big buyer that could have potentially bought all the capacity, the firm chose not to engage to prevent the buyer's potential ability to "*leverage and dictate*."

Collaboration with larger and/or more powerful partners is also associated with asymmetric engagement complexity, which arises when one partner tries to engage another, noninterested partner. For example, E5 said that although their firm required highly advanced technical solutions, it experienced complexity in engaging with big innovative suppliers, as it could not offer the required volume. The situation was also similar on the supplier side, described by supplier S1 as "*you are knocking on the door of customers, and they say, 'No, sorry; you know, I'm not interested*.'" This condition can be related to the periodic attractor of the resonance state in which a partner tries to "find the right frequency" to resonate with an uninterested partner. For example, E5 engaged with larger and more innovative suppliers by resonating with their need for technology testing.

The final identified relationship complexity manifests within firm boundaries. It relates to the existence of an invisible interface, either between departments (e.g. R&D and sourcing) or between specific departments and external partners (e.g. R&D and the supplier base). It may result in a "gray area" that is hard to capture or manage. Interviewee B1 pointed out a challenge related to idea implementation within their firm when innovative ideas were evaluated through emails that would "*not necessarily get recorded; not to mention, it is not open and transparent for everyone*." An interviewee from P1 shared that due to invisible relationships between its R&D and suppliers, "*a lot of suppliers who have technologies that might become important to us contact our R&D folks directly, which is sometimes challenging to control from a supply chain point of view.*" In response to this complexity, a firm might navigate toward a point attractor in the form of connecting through an intermediary. Doing so ensures that the previously disconnected and invisible parts of the system are illuminated by establishing a designated node or employee tasked with ensuring that information is systematically channeled and managed.

4.2.2 Temporal complexity. Temporal complexity was one of the most challenging complexities faced by firms in the sample. Many interviewees discussed the difficulty of accurately estimating the value of new products or processes or "*hunting out the hidden value*" (V1). For instance, a representative from B1 reflected on a case in which a buyer requested customized packaging. Although the concept was innovative and appeared viable, subsequent research and experimentation led to the realization that the associated value would be limited due to the absence of a system to standardize it.

This complexity, associated with accurately predicting an innovation's potential with current knowledge, may lead firms to prematurely dismiss technologies that could be extremely valuable in the future. For example, an interviewee from M4 shared that a skilled individual had approached him from a major company and proposed an idea for a better solution, which his company rejected. The interviewee facilitated this individual's establishment of their own supply business, successfully developing a superior product, outperforming existing solutions, and gaining market dominance. This case is an example of a strange attractor in the form of weak ties, a recurring theme in our analysis.

Another temporal complexity, innovation readiness rift, implies that even when an innovation has clear value, stakeholders may not be ready for it. For example, A2 reported a disconnect with customers, with their firm being "*sometimes too advanced in driving innovation*" and bringing to market products that "*may not yet be valued by customers*." Notably, "stakeholders" refers not only to a product's users but can also include a firm's departments. The representative from M4 recounted an instance of this complexity internally, where an innovation developed in collaboration with a supplier was met with resistance from the R&D team.

These complexities have been linked to the periodic attractor in the form of temporal alignment, wherein a firm tries to synchronize its future vision with its stakeholders, for example, through technology roadmaps developed during regular collaboration. Another periodic attractor observed in the "timing of new product or process value estimation" involves knowledge recalibration, where a firm adjusts its perspective and actions over time as new information is obtained.

A commonly faced temporal complexity in the sample network was the stretched innovation cycle. Interviewees pointed out that not only was innovation taking longer to implement than anticipated but that it was also hard to predict its future impact. According to an interviewee from P3, in their firm's context, innovation was often "*something that stays there for the next 10–20 years. Therefore, it is very difficult to change the past, but when something takes action in the present, it will stay for a long time in the future*." The complexity of the stretched innovation cycle has been associated with the periodic attractor of observational learning when a firm intentionally chooses to adopt a more passive role initially, observing the successes and failures of other businesses in a new domain before making its own move.

The final temporal complexity identified relates to mismatched development stages within the SN. This complexity manifests as asynchrony in the maturity levels among different network parts. For instance, a representative from M1 recounted their experience collaborating with partners from another region who, despite having a remarkable vision, were relatively underdeveloped in terms of maturity. Over time, M1 was able to enhance maturity and synchronize the SN segment in which it was embedded. We did not observe any attractor associated with this complexity.

4.2.3 Dynamic complexity. Unlike temporal complexity, dynamic complexity is associated with the continuously changing environment of the SNs in which firms operate. Although this complexity appears to be less immediate than temporal complexity, it seems to have longer-lasting consequences. One of the most common dynamic complexities is related to uncertainty about activities taking place in other parts of an SN. The interviewees highlighted a lack of visibility and transparency on both the supplier and buyer sides. While most understood their direct suppliers' operations, they rarely mapped the extended SN. Although this does not directly lead to negative consequences, firms often view this situation with a layer of anxiety and anticipation of technological disruption. This complexity has been linked to the periodic attractor of knowledge recalibration, which includes a firm's anticipatory measures to recalibrate its knowledge in response to changing circumstances and to remain aligned with or ahead of developments within a network.

This complexity has been related to the strange attractor in the form of actor reconfiguration. This suggests that more ambiguous segments of a network may adapt in somewhat unpredictable ways. For instance, a representative from V5 recounted that their firm had entered into an innovative project with its component supplier. However, unexpectedly, the supplier declared bankruptcy. The project's prospects seemed to fail until, in another unexpected development, the bankrupt supplier was acquired. The new owner chose to continue the innovative project, leading to its success despite significant reconfigurations, such as changing the supply chain to another country.

Another significant dynamic complexity that extends from the network to the firm level is selection pressure. This requires firms to continuously monitor network developments and defend their niches in the competitive landscape. A P3 representative observed, "*Companies, like people, change constantly. Some may be at the top and then, due to various factors, can no longer stay there. Meanwhile, other companies that you wouldn't expect keep improving and manage to rise to the top*." Most firms in our study acknowledged the tight link between innovation and selection pressure, recognizing the necessity of investing substantially in R&D

to maintain their network positions. Although the effects of selection pressure may be gradual, firms often respond with swift actions—a strategy many describe as "survival." This complexity has been linked to a point attractor of convergence to the central actor.

The dynamic complexity of innovation blocking is related to the patenting of an innovation, in which firms are required to "*be careful not to go too far with product development projects where patent obstacles from competitors may arise*" (E3). This complexity is evidenced in the case described by M4, when a big producer that did not have a strong understanding of the industry in which M4 operated took out a patent that would have restricted other companies in the industry from using their innovation. The interviewee also emphasized this complexity as associated with the ever-changing landscape of patents in the industry. We have not identified an attractor related to this complexity.

The final dynamic complexity relates to path dependency. While sometimes the most logical solution is to change the course of action, firms prefer to continue the familiar route. For instance, the representative of A2 described this dynamic complexity in the context of digitalization "*If someone has always been using the bus to go to places—go to work or go shopping—and you sell them a car, it may happen that because they are so deeply accustomed to they did things, they would drive the same route as they did previously, when they went by bus.*" We have not identified an attractor related to this complexity.

4.2.4 Operational complexity. The operational complexity observed within the SN and its actors stems from the necessity of establishing and maintaining effective product and process innovation within and across SN partnerships. Our sample's most prevalent form of operational complexity was associated with required coordination. This complexity was especially pronounced in the context of large-scale equipment manufacturing. As E1 explained, "*It is tremendously laborious when you have got such a large-scale, big manufacturing process to tailor it down to smaller components*." While many firms recognized the need for a systemic approach to the coordination of supplier-driven innovation, implementing such a process proved to be challenging. Interviewee from M8 explained, "*Yeah, it is difficult. Of course, we have 20 million items in [firm name], and the idea can be for any of those items. [. . .] The idea can be very small but very important; it can be easy to implement or difficult to implement. It can be a breakthrough idea or an incremental idea.*" This complexity is related to a strange attractor of the cross-applicability of technologies and components when a firm uses process developments from other industries to optimize and streamline its processes.

Another operational complexity we identified pertains to internal innovation acquisition and dissemination. This complexity appears strongly linked to process innovation and the substantial effort needed for holistic implementation, mainly when a firm and its departments, such as R&D, are geographically dispersed. It also concerns the redundancy that arises from the simultaneous existence of multiple information channels within a firm. This operational complexity is exemplified by the point attractor of connecting through an intermediary. B1 provided an example of the complexity of sharing process solutions between mills. As the interviewee described, a mill that had achieved process innovation often focused on implementing the solution internally. To connect the system parts and spread innovation, B1 employed intermediaries, known as "solution advisors," who worked with the mill's innovators to ensure that the solution was standardized—or "productized"—for application in other mills. Another attractor addressing innovation retention is the point attractor of novel ideas storing, where a firm stores ideas and innovations, that may originate both internally and externally, for future use.

Several interviewees highlighted the operational complexity encountered when firms took deliberate actions to internalize innovations that had previously been developed in collaboration, such as with a supplier. This trend was evident among some of the larger manufacturing firms in our sample and could be attributed to factors such as the need for advanced certification (E4) or exceptional quality (E3). Notably, this complexity manifested in a growing preference among firms to acquire start-ups rather than to maintain collaborative supplier relationships. We have also observed the low popularity of small-sized firms from the network analysis reported in Section 4.1. We have not identified an attractor related to this complexity.

The final operational complexity relates to the economic viability of new solutions and the accurate expectation of associated financial commitments. Interviewees noted that many innovative solutions did not initially succeed economically. For instance, P1 observed that lithium-ion batteries had only recently become more economically viable. The challenge of assessing economic feasibility is compounded by expectations that often do not meet reality. This complexity is particularly pronounced in collaborative innovation with universities, where monetary value is seldom the primary focus. The economic viability complexity has been related to the periodic attractor of the preemptive innovation cycle, when innovation starts before feedback from the market is received or in parallel.

4.2.5 Structural complexity. Structural complexity was the least pronounced in our analysis. Some interviewees highlighted the complexity arising from an extensive SN, which encompassed the need to manage a broad supplier base and navigate supplier triads. An interviewee from P1 pointed out that the company's stretched SN, primarily located in Asia, required increased coordination and rigorous risk control. This complexity is linked to the point attractor of connecting through an intermediary, wherein a firm seeks to engage with a highly connected actor to draw an extended network closer or get better visibility. An interviewee from M5 revealed that the company's interest in the renewables market led it to purposefully alter its SN. It had an opportunity to supply to a large buyer; however, its production and network lacked capacity, and it needed technology. As a result, it connected the network by establishing a strategic joint venture with a smaller engineering firm. For example, M5's actions were to create a new stable state in which various participants of the SN—such as the firm itself, its competitor, the multinational steel manufacturer, and the smaller engineering company—were coalescing around this emerging opportunity in the renewables sector.

Several interviewees highlighted supply base complexity, explicitly pointing to cultural, language, and time-zone differences that could impact collaboration. For instance, a representative from M5 noted that while partnership with suppliers in Nordic countries was often more straightforward, innovation could not be expected to come solely from that region. Consequently, there was a need to adapt to the cultural diversity within the company's varied supplier bases, which included M5's partners in African and Asian countries. Notably, most interviewees did not view the geographically distributed supplier base and the associated cultural diversity as barriers to effective collaboration but rather as complexity that encouraged adaptation by both themselves and their suppliers. However, in certain instances of highly technical and regulated supplier-driven innovation, a firm might choose suppliers based on the proficiency of its R&D personnel in English. Notably, this complexity may be related to cultural reflection within firms and the strange attractor of societal–cultural reflectivity. For instance, a hierarchical decision-making structure within some suppliers may reflect the cultural hierarchical norms of a region. This complexity may also be associated with the attractor of systemic disentanglement, where firms intentionally streamline their supply base to diminish the inflow of ideas and simplify the complexity of coordination.

Finally, the geographical variance across the firm's locations adds a layer of complexity to innovation. This complexity was linked to the necessity of ensuring consistent categorization of innovative suppliers and preventing conflicts among R&D teams in different locations. An interviewee from V3 noted that operations could vary significantly within the same company based on location. Some firm representatives also observed that there might be greater resistance to adopting innovations developed by a team from the same company but in a different location to, for instance, innovations created by a start-up, suggesting that this complexity might be associated with high internal competition.

5. Discussion

In this section, we first abstract our results and holistically discuss how dynamic attractors and innovation complexities manifest in SN at various strata. We then introduce and discuss the conceptual framework of balancing chaos and order in an innovative SN, along with a set of working propositions derived from our results.

5.1 Dynamic attractors in an innovative supply network

Several *point attractors* associated with innovation complexities were identified. Some of these, such as “systemic disentanglement,” are more visible at the SN level. For instance, as a firm’s innovative supplier base expands, reflecting structural innovation complexity, the SN system and its actors may adapt by phasing out less prominent relationships to streamline processes, thereby establishing a stable state. Others are more evident at the firm level. For example, the “storing of novel ideas” arises in response to operational complexity and leads to a firm’s adaptation by storing innovative ideas within its knowledge base. Furthermore, point attractors were the most frequently observed attractors in our research.

The *periodic attractors* are cyclically repeating behavior patterns observed at the SN and firm strata. These can be regular, such as “knowledge recalibration,” which in our results often occurred in regular cycles (e.g. every year), and irregular, as in the case of the “resonance state,” which can happen when the corresponding complexity becomes more pronounced. This type of attractor is often associated with temporal complexity at the firm level, as the firm adapts to the temporal cycles and rhythms that cascade down from higher SN levels.

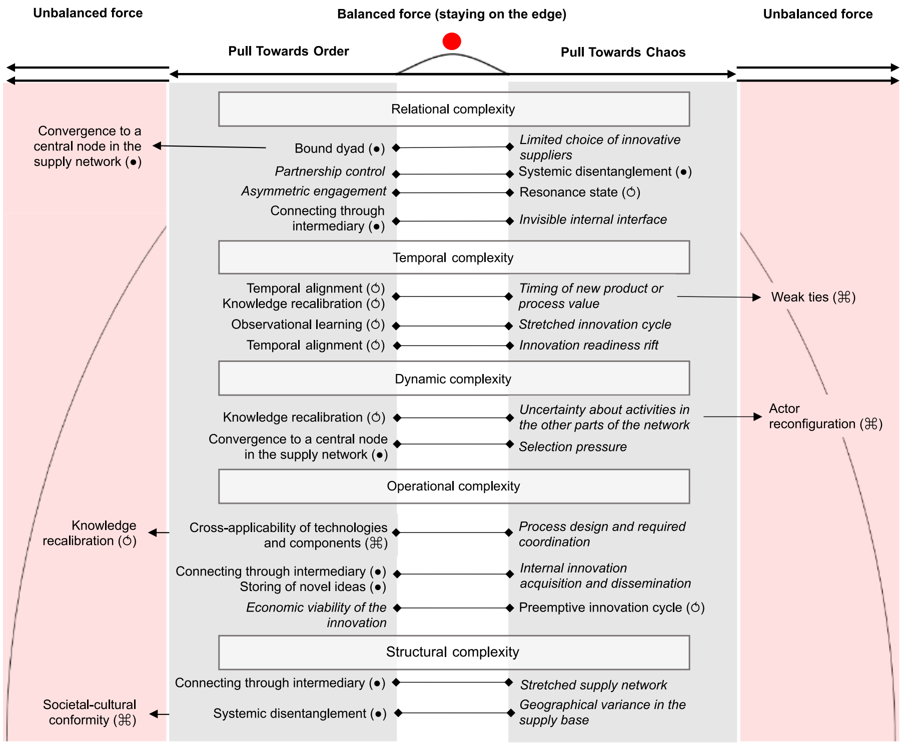
Finally, *strange attractors* were the least common type of attractors identified in our study. These attractors most frequently appear at the SN level and cascade down to the firm level. Importantly, although strange attractors may seem unpredictable, they often have significant and lasting impacts on the complex adaptive behaviors of the SN system. Our analysis found that companies and interviewees usually perceived strange attractors as surprising events with substantial positive or negative but seldom mild impacts. For example, firms struggling with the operational complexity of process design may be pulled by a strange attractor of the “cross-applicability of technologies and components,” potentially resulting in firms addressing the complexity by utilizing the process design developed elsewhere in SN, leading to significant positive adaptation.

5.2 Conceptual framework of chaos and order balancing in an innovative supply network

To develop the conceptual framework, we examined the interrelationships between innovation complexities and attractors. Specifically, we analyzed whether they drive an SN system toward order or chaos and how they are balanced. An example of this balancing is the structural complexity of a stretched SN, which leans toward chaos due to heightened complexity and an inflow of information and can achieve balance through the point attractor of “connecting through an intermediary.” This point attractor functions by steering the system toward order while maintaining the level of chaos necessary for optimal innovation.

Based on the results of this abstraction for all complexities and attractors, we developed the conceptual framework presented in Figure 2. This framework extends Figure 1 and provides a detailed overview of the complexities and attractors that firms encounter to stay “on the edge of chaos.” Based on our findings and guided by complexity theory, we suggest that it is possible to navigate existing innovation complexities effectively by understanding existing systemic attractors and navigating them strategically.

Figure 2 also illustrates that although most innovation complexities and attractors may achieve or approach a balanced state, we observed five SN system states in which the forces remain unbalanced. These instances drive a hierarchically nested SN system toward a less desirable state of unbalanced order or chaos. Based on this discovery, we offer a series of propositions.



Note(s): The complexities are indicated in italics; (●) point attractor, (⥀) periodic attractor, (⌘) strange attractor
Source(s): Authors' own creation

Figure 2. Conceptual framework of chaos and order balancing in an innovative SN

First, when faced with the relational complexity of a limited choice of innovative suppliers, we observed that firms in an SN balanced this systemic force with the point attractor of the "bound dyad." Our network analysis identified desirable suppliers, such as S1 and P1, which offered novel solutions. At a lower level, firms entered into stable "bound dyad" relationships with these actors. At the SN level, we noted the emergence of another point attractor: "convergence to a central node in the network." This stable state exemplifies an unbalanced order characterized by a highly centralized network and potentially reduced innovative performance due to knowledge redundancy. Based on these observations, we propose the following:

P1. An innovative SN affected by the relational complexity of the "limited choice of innovative suppliers" at the firm level is drawn toward the potentially unbalanced ordered state of the point attractor "convergence to the central node in SN" at the SN level.

Proposition 1 is consistent with Sting *et al.*'s (2019) notion of "temporary deembedding," which posits that firms should deliberately loosen and subsequently reestablish embedded ties. Our study further suggests that a network may experience a decline in creative capacity over time as it becomes more stable and that strategically reducing tie density could enhance its overall innovative performance.

Second, firms within an innovative SN face the temporal complexity of the "timing of new product or process value." This complexity is associated with the periodic attractors of "knowledge recalibration" and "temporal alignment," which guide the system toward a more ordered state. However, this complexity can also connect with the strange attractor of "weak ties," which can disrupt the system and push it toward unbalanced chaos, such as accelerating the introduction of innovations into the market. While this may lead to an unbalanced state of chaos, it often results in enhanced SN innovation and adaptability, particularly when the impact is contained. We propose the following:

P2. An innovative SN affected by the temporal complexity of "timing of a new product or process value" at the firm level is drawn toward a potentially unbalanced chaotic state of strange attractor, "weak ties," at the SN level.

Proposition 2 aligns with Capaldo (2007), who highlighted the significance of a firm's capacity to integrate a broad periphery of heterogeneous weak ties. We further suggest that the weak ties' attractor, although beneficial for promoting SN innovation, may disrupt the ordered timing of new product or process value. Additional control may be necessary to prevent this disruption from leading to strongly unbalanced chaos.

Third, an innovative SN is influenced by the dynamic complexity of uncertainty about activities in other parts of the network. This complexity is linked with the periodic attractor "knowledge recalibration," a state in which firms periodically update their knowledge of the network. However, this complexity is also related to the strange attractor of "actor reconfiguration," where the SN may disrupt and reconfigure unexpectedly. Our findings suggest that this attractor can lead the SN system into unproductive chaos and diminished SN innovation, particularly during periods of high instability. Thus, we propose the following:

P3. An innovative SN affected by the dynamic complexity of "uncertainty about activities in the other parts of the network" at the firm level is drawn toward a potentially unbalanced chaotic state of strange attractor, "actor reconfiguration," at the SN level.

Fourth, firms in an SN encounter operational complexity associated with the need to design and coordinate their processes. As a result, they balance this chaotic pull by borrowing existing best practices (e.g. solutions for mass production). The cross-applicability of technologies and components naturally leads to periodic knowledge recalibration, as it requires an understanding of different fields and contexts. However, this may pull the system into an unproductive order where the process becomes too rigid or confined to a borrowed perspective. This relationship was confirmed by examples of standardization and lower SN innovation. As a result, we propose the following:

P4. An innovative SN affected by the operational complexity of "process design and required coordination" at the firm level is drawn toward a potentially unbalanced ordered state of periodic attractor, "knowledge recalibration," at the SN level.

Finally, firms may encounter structural complexity arising from the diversity of cultures or "geographical variance in the supply base" and try to balance it through the point attractor of systemic disentanglement. However, the emergence of the point attractor "societal–cultural conformity" within a condensed network may result in a tendency toward order. While a firm may attempt to alter its network to reduce structural complexity, societal–cultural conformity—whereby the supplier aligns its culture with the surrounding environment—may result in higher homophily within SN and lower SN innovation. Therefore, we propose the following:

P5. An innovative SN affected by the structural complexity of "geographical variance in the supply base" at the firm level is drawn toward a potentially unbalanced ordered state of strange attractor, "societal–cultural conformity," at the SN level.

5.3 Contribution to theory

This study makes several scholarly contributions. First, it enriches complexity theory by defining and holistically examining the five types of innovation complexities within SN. Previous research has delineated the complexities of innovation (e.g. Garud *et al.*, 2013) and explored the various dimensions of SN complexity and their impact on firm innovation (e.g. Choi and Krause, 2006; Sharma *et al.*, 2020). Our study synthesizes disparate perspectives on innovation complexities and presents a novel viewpoint on how systemic processes within SN influence and are influenced by the emergence of innovation.

Second, this study further advances complexity theory by explicitly theorizing the dynamic attractors (Platje and Seidel, 1993; Anderson, 1999; Pryor and Bright, 2014) within complex and adaptive SN (Choi *et al.*, 2001). Previous research has acknowledged attractors as a means to harness the potential of creative chaos (e.g. Jayanthi and Sinha, 1998; Dolan *et al.*, 2003). However, to our knowledge, this is the first study to thoroughly identify and examine these attractors and elucidate their impact on innovation processes within SN. We extend the theoretical understanding by employing an analogy-based approach, transferring insights from the natural sciences to the context of SN, thereby creating new meaning structures through a "creative blend" of concepts from diverse fields, as proposed by Gruner and Power (2023).

Third, this study suggests achieving an optimal level of innovation within SN by *navigating* rather than managing or resolving innovation complexities. Although simple in concept, this approach provides a distinct perspective on innovation within SNs, emphasizing that balance must be maintained by examining existing attractors and complexities and avoiding unproductive, imbalanced states of order or chaos.

Finally, this study augments and expands upon existing SN research (e.g. Kim *et al.*, 2011; Bellamy *et al.*, 2014) by conducting a temporal network analysis with TERGM, an approach novel in the supply management field. It elucidates the micro-foundations of network development and patterns of evolution over time. Furthermore, it adopts a multilevel perspective that examines complexities and attractors at various strata, including the firm and network levels, thereby enriching the discourse on multilevel SN theory (Carter *et al.*, 2015).

5.4 Contribution to practice

This research also contributes to practice. It gives managers a comprehensive understanding of the innovation complexities within an SN, detailing its manifestations and implications from a holistic perspective. The research suggests that achieving optimal innovation performance is "balancing at the edge," requiring a broad view of the SN in which a firm is embedded and a mastery of finding a balance between order and chaos. Therefore, recognizing an SN's adaptive nature is essential for moving from a control mindset to an emergent mindset toward its processes. In addition, managers should understand the presence of attractors in relation to different innovation complexities and how they can lead to unwanted states of disequilibrium when processes become too rigid or chaotic. Therefore, to achieve a balanced state at the edge, it is necessary to understand how prominent these complexities and attractors are for firms and the SNs in which they are embedded and to make the decision to navigate them while allowing for the natural adaptation of the system.

Additionally, the propositions offer a set of practical implications for managers. Practitioners should strategically reassess partnerships to prevent overcentralization that hampers innovation and loosens the embedded ties to foster creativity in an SN. For proper timing, managers should acknowledge and judiciously utilize weak ties to promote, but not overwhelm, innovation. Managers should regularly update their network knowledge to reduce uncertainty and maintain agility when faced with emergent network reconfigurations. It is also essential to avoid excessive standardization when adopting external best practices, maintain applicability for new solutions, and stay cognizant of the cultural dynamics affecting SN.

Collectively, these insights inform the balanced interplay between order and chaos in driving innovation in SNs.

5.5 Limitations and future research

Our research has certain limitations. The conclusions are limited, as the SN studied was not global and was mostly located in a single region. While this allowed for the depth of the analysis, we recognize that future research should test the derived conclusions in broader settings. One opportunity is to perform a large-scale empirical study that tests the interplay between complexities and attractors. Another limitation of the research is the focus on manufacturing companies. While we extended our analysis to include other types of organizations, the study's findings may be less applicable to, for example, service-oriented SNs.

Furthermore, we must acknowledge a potential limitation due to survivorship bias. Our approach involved inquiring about suppliers from current representatives and subsequently tracing their historical relationships. However, this method may have overlooked central players that ceased operations or became less relevant. Despite our efforts in data triangulation, which included incorporating multiple sources of relationship data, this limitation may persist.

The results of this research offer several opportunities for future research. For example, future studies may utilize our propositions as testable hypotheses since they imply a cause-and-effect relationship that can be observed and measured within SNs. Moreover, the propositions present a balanced view of the potential benefits and downsides of order and chaos within SNs. Future studies may address the conditions under which the proposed effects are more likely to occur. For instance, under what conditions do weak ties lead to beneficial rather than detrimental chaos? Finally, we invite future research to extend the insights of this study and the work of Jayanthi and Sinha (1998) to deepen the understanding of systemic attractors within SN. A further focus on domains such as environmental sustainability (Nair *et al.*, 2016) is recommended, which, in our view, can only be effectively addressed through a comprehensive and holistic CAS approach.

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Supplementary material

The supplementary material for this article can be found online.

Corresponding author

Iryna Malacina can be contacted at: iryna.malacina@lut.fi